

The Clustering of XMM-*Newton* Hard X-ray Sources

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ABSTRACT

This paper presents the clustering properties of hard (2-8 keV) X-ray selected sources detected in a wide field ($\approx 2 \text{ deg}^2$) shallow [$f_X(2 - 8 \text{ keV}) \approx 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$] and contiguous XMM-*Newton* survey. We perform an angular correlation function analysis using a total of 171 sources to the above flux limit. We detect a $\sim 4\sigma$ correlation signal out to 300 arcsec with $w(\theta < 300'') \simeq 0.13 \pm 0.03$. Modeling the two point correlation function as a power law of the form $w(\theta) = (\theta_0/\theta)^{\gamma-1}$ we find: $\theta_0 = 48.9_{-24.5}^{+15.8}$ arcsec and $\gamma = 2.2 \pm 0.30$. Fixing the correlation function slope to $\gamma = 1.8$ we obtain $\theta_0 = 22.2_{-8.6}^{+9.4}$ arcsec. Using Limber's integral equation and a variety of possible luminosity functions of the hard X-ray population, we find a relatively large correlation length, ranging from $r_0 \sim 9$ to $19 h^{-1} \text{ Mpc}$ (for $\gamma = 1.8$ and the *concordance* cosmological model), with this range reflecting also different evolutionary models for the source luminosities and clustering characteristics. The relatively large correlation length is comparable to that of extremely red objects and luminous radio sources.

Subject headings: galaxies: active — quasars: general — surveys — cosmology: observations — large-scale structure of the universe — X-rays: diffuse background

1. Introduction

It is well known that the study of the distribution of matter on large scales, using different extragalactic objects provides important constraints on models of cosmic structure formation. Since Active Galactic Nuclei (AGN) can be detected up to very high redshifts they provide information on the underlying mass distribution as well as on the evolution of large scale structure (cf. Hartwick & Schade 1989; Basilakos 2001 and references therein).

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The traditional indicator of clustering, the angular two-point correlation function, is a fundamental and simple statistical test for the study of any extragalactic mass tracer and is relatively straightforward to measure from observational data. The overall knowledge of the AGN clustering using X-ray data comes mostly from the soft ($\leq 3\text{keV}$) X-ray band (Boyle & Mo 1993; Vikhlinin & Forman 1995; Carrera et al. 1998; Akylas, Georgantopoulos, Plionis, 2000; Mullis 2002), which is however biased against absorbed AGNs. Hard X-ray surveys ($\geq 2\text{keV}$) play a key role in our understanding of how the whole AGN population, including obscured (type II) AGNs, trace the underlying mass distribution. Furthermore, understanding the spatial distribution of type II AGNs is important since they are among the main contributors of the cosmic X-ray background (Mushotzky et al. 2000; Hasinger et al. 2001; Giacconi et al. 2002).

Recently, Yang et al. (2003) performing a counts-in cells analysis of a deep ($f_{2-8\text{keV}} \sim 3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$) *Chandra* survey in the Lockman Hole North-West region, found that the hard band sources are highly clustered with $\sim 60\%$ of them being distributed in overdense regions. The XMM-*Newton* with ~ 5 times more effective area, especially at hard energies, and ~ 3 times larger field of view (FOV) provides an ideal instrument for clustering studies of X-ray sources.

In this paper we estimate for the first time the angular correlation function of the XMM-*Newton* hard X-ray sample. Using Limber’s equation and different models of the luminosity function for these sources we derive the expected spatial correlation function which we compare with that of a variety of extragalactic populations. Hereafter, all H_0 -dependent quantities will be given in units of $h \equiv H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. The Sample

The hard X-ray selected sample used in the present study is compiled from the XMM-*Newton*/2dF survey. This is a shallow (2-10 ksec per pointing) survey carried out by the XMM-*Newton* near the North Galactic Pole [NGP; RA(J2000)=13^h41^m; Dec.(J2000)=00°00′] and the South Galactic Pole [SGP; RA(J2000)=00^h57^m, Dec.(J2000)=−28°00′] regions. A total of 18 XMM-*Newton* pointings were observed equally split between the NGP and the SGP areas. However, a number of pointings were discarded due to elevated particle background at the time of the observation. This results in a total of 13 usable XMM-*Newton* pointings covering an area of $\approx 2 \text{ deg}^2$. A full description of the data reduction, source detection and flux estimation are presented by Georgakakis et al. (2003, 2004). For the 2-D correlation analysis presented in this paper we use the hard (2-8 keV) band catalogue of the XMM-*Newton*/2dF survey. This comprises a total of 171 sources above the 5σ detection

threshold to the limiting flux of $f_X(2 - 8 \text{ keV}) \approx 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$. Note that our hard X-ray sources comprise of a mixture of QSO's and relatively nearby ($z < 0.8$) galaxies with red colours $g - r > 0.5$ which are most probably associated with obscured low-luminosity AGN (Georgantopoulos et al. 2004).

3. Correlation function analysis

3.1. The angular correlation

The clustering properties of the hard X-ray selected sources are estimated using the two point angular correlation function $w(\theta)$ defined by $dP = n^2[1 + w(\theta)]d\Omega_1 d\Omega_2$, where dP is the joint probability of finding two sources in the solid angle elements $d\Omega_1$ and $d\Omega_2$ separated by angle θ and n is the mean surface density of sources. For a random distribution of sources $w(\theta)=0$. Therefore, the angular correlation function provides a measure of galaxy density excess over that expected for a random distribution. A variety of estimators of $w(\theta)$ have been used over the years (cf. Infante 1994).

In the present study we use the estimator (cf. Efstathiou et al. 1991):

$$w(\theta) = f(N_{DD}/N_{DR}) - 1, \quad (1)$$

where N_{DD} and N_{DR} is the number of data-data and data-random pairs respectively at separations θ and $\theta + d\theta$. In the above relation f is the normalization factor $f = 2N_R/(N_D - 1)$ where N_D and N_R are the total number of data and random points respectively. The uncertainty in $w(\theta)$ is estimated as $\sigma_w = \sqrt{(1 + w(\theta))/N_{DR}}$ (Peebles 1973). To account for the different source selection and edge effects, we have produced 100 Monte Carlo random realizations of the source distribution within the area of the survey by taking into account variations in sensitivity which might affect the correlation function estimate. Indeed, the flux threshold for detection depends on the off-axis angle from the center of each of the XMM-*Newton* pointings. Since the random catalogues must have the same selection effects as the real catalogue, sensitivity maps are used to discard random points in less sensitive areas (close to the edge of the pointings). This is accomplished, to the first approximation, by assigning a flux to the random points using the Baldi et al. (2002) 2-10 keV $\log N - \log S$ (after transforming to the 2-8 keV band assuming $\Gamma = 1.7$). If the flux of a random point is less than 5 times the local *rms* noise (assuming Poisson statistics for the background) the point is excluded from the random data-set. We note that the Baldi et al. (2002) $\log N - \log S$ is in good agreement with the 2-8 keV number counts estimated in the present survey. This is demonstrated in Figure 1 where we plot our differential number counts and the best fit relation of Baldi et al. (2002). Note that we have tested that our random

simulations reproduce both the off-axis sensitivity of the detector as well as the individual field $\log N - \log S$.

We apply the correlation analysis evaluating $w(\theta)$ in logarithmic intervals with $\delta \log \theta = 0.05$. The results are shown in Figure 2, where the line corresponds to the best-fit power law model $w(\theta) = (\theta_o/\theta)^{\gamma-1}$ using the standard χ^2 minimization procedure in which each correlation point is weighted by its error. We find a statistically significant signal with $w(\theta < 300'') \simeq 0.13 \pm 0.03$ at the 4.3σ and $\sim 2.7\sigma$ confidence level using Poissonian or bootstrap errors respectively. Note that the bootstrap errors probably overestimate the true uncertainty, especially in sparse samples (Fisher et al 1994). Therefore the true significance level is somewhere in between the above two values.

In the insert of Figure 2 we present the iso- $\Delta\chi^2$ contours (where $\Delta\chi^2 = \chi^2 - \chi_{\min}^2$) in the $\gamma - \theta_o$ plane. The contours correspond to 1σ ($\Delta\chi^2 = 2.30$) and 2σ ($\Delta\chi^2 = 6.17$) uncertainties, respectively. The best fit clustering parameters are:

$$\theta_o = 48.9_{-24.5}^{+15.8} \text{ arcsec} \quad \gamma = 2.2 \pm 0.30 \quad (2)$$

where the errors correspond to 1σ ($\Delta\chi^2 = 2.30$) uncertainties. Fixing the correlation function slope to its nominal value, $\gamma = 1.8$, we estimate $\theta_o = 22.2_{-8.6}^{+9.4} \text{ arcsec}$ ³. Note that our results do not suffer from the *amplification bias* which results from merging close source pairs when the PSF size is larger than their typical separation (see Vikhlinin & Forman 1995). This is because the estimated θ_o values are much larger than the XMM-Newton PSF size of $6''$ FWHM.

Another systematic effect that could bias the angular 2-point correlation function is that introduced by the so called *integral constraint*. This results from the fact that the correlation function is estimated from a limited area, which in turn implies that over the area studied the relation $\int \int w(\theta_{12}) d\Omega_1 d\Omega_2 = 0$ should be satisfied. We can attempt to estimate the resulting underestimation of the true correlation function by calculating the quantity: $W = \int d\Omega_1 \int d\Omega_2 w(\theta_{12}) / \int d\Omega_1 \int d\Omega_2$. Clearly, evaluating W necessitates *a priori* knowledge of the angular correlation function. A tentative value of W using a range of $w(\theta)$ given by varying within 1σ our results (eq.2) is: $W \simeq 0.02$. By adding W to our estimated (raw) $w(\theta)$ and fitting again the model correlation function we find:

$$\theta_o \simeq 44 \pm 20 \text{ arcsec} \quad \gamma \simeq 2 \pm 0.25, \quad (3)$$

consistent within the errors, with our uncorrected results (eq. 2). If we fix $\gamma = 1.8$ we obtain

³The robustness of our results to the fitting procedure was tested using different bins (spanning from 10 to 20) and no significant difference was found.

$\theta_o = 28 \pm 9$ arcsec. Due to the small effect of the *integral constraint* correction we will use in the rest of the paper our *raw* $w(\theta)$ estimates.

Our results show that hard X-ray sources are strongly correlated, even more than the soft ones (see Vikhlinin & Forman 1995; Yang et al. 2003; Basilakos et al. in preparation). Our derived angular correlation length θ_o is in rough agreement, although somewhat smaller (within 1σ) with the *Chandra* result of $\theta_o = 40 \pm 11$ arcsec (Yang et al. 2003). The stronger angular clustering with respect to the soft sources could be either due to the higher flux limit of the hard XMM-*Newton* sample, resulting in the selection of relatively nearby sources, or could imply an association of our hard X-ray sources with high-density peaks of the underline matter distribution. To test the latter suggestion we have measured the cluster - hard X-ray sources cross-correlation function ($w_{c,hard}$) using either the Goto et al. (2002) clusters, detected in the multicolour optical SDSS data, or the X-ray clusters that we have detected on our fields (Gaga et al. in preparation). We find no significant cross-correlation signal [$w_{c,hard}(\theta < 300'') \simeq -0.15 \pm 0.19$], a fact that weakens the suggestion of association of the hard X-ray sources with high-density peaks. However, we must stress that the null result could be artificial, due to small number statistics.

3.2. The spatial correlation length using $w(\theta)$

The angular correlation function $w(\theta)$ can be obtained from the spatial one, $\xi(r)$, through the Limber transformation (Peebles 1980). If the spatial correlation function is modeled as

$$\xi(r, z) = (r/r_o)^{-\gamma} (1+z)^{-(3+\epsilon)}, \quad (4)$$

then for a flat Universe the amplitude θ_o in two dimensions is related to the correlation length r_o (see Efstathiou et al. 1991) in three dimensions through the equation:

$$\theta_o^{\gamma-1} = H_\gamma r_o^\gamma \left(\frac{H_o}{c} \right)^\gamma \int_0^\infty \left(\frac{1}{N} \frac{dN}{dz} \right)^2 \frac{E(z)}{x^{\gamma-1}(z)} (1+z)^{-3-\epsilon+\gamma} dz, \quad (5)$$

where $x(z)$ is the proper distance, $E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$ is the element of comoving distance and $H_\gamma = \Gamma(\frac{1}{2})\Gamma(\frac{\gamma-1}{2})/\Gamma(\frac{\gamma}{2})$. Note that if $\epsilon = \gamma - 3$, the clustering is constant in comoving coordinates (comoving clustering) while if $\epsilon = -3$ the clustering is constant in physical coordinates. We perform the above inversion in the framework of either the *concordance* Λ CDM cosmological model ($\Omega_m = 1 - \Omega_\Lambda = 0.3$, $H_o = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$) or the Einstein-de Sitter model.

The redshift distribution dN/dz and the predicted total number, N , of the X-ray sources which enter in eq. 5 can be found using the hard band luminosity functions of Ueda et al.

(2003) and of Boyle et al. (1998). We also use different models for the evolution of the hard X-ray sources: a pure luminosity evolution (PLE) or the more realistic luminosity dependent density evolution (LDDE; Ueda et al 2003). In Figure 3 we show the expected redshift distributions of the hard X-ray sources for three different luminosity functions and evolution models. Both the Boyle et al (1998) and Ueda et al (2003) luminosity functions with pure luminosity evolution give relatively similar dN/dz distributions. However, the LDDE model gives an dN/dz distribution shifted to much larger redshifts with a median redshift of $\bar{z} \simeq 0.75$ (see also Table 1).

For the comoving clustering model ($\epsilon = \gamma - 3$) and using the LDDE evolution model, we estimate the hard X-ray source correlation length to be: $r_o = 19 \pm 3 \ h^{-1} \text{ Mpc}$ and $r_o = 13.5 \pm 3 \ h^{-1} \text{ Mpc}$ for $\gamma = 1.8$ and $\gamma = 2.2$ respectively. While if $\epsilon = -3$ the corresponding values are: $r_o = 11.5 \pm 2 \ h^{-1} \text{ Mpc}$ and $r_o = 6 \pm 1.5 \ h^{-1} \text{ Mpc}$, respectively. In Table 1, we present the values of the correlation length, r_o , resulting from Limber’s inversion for different luminosity function and evolution models.

These estimated clustering lengths (for $\gamma = 1.8$) are a factor of $\gtrsim 2$ larger than the corresponding values of the Lyman break galaxies (Adelberger 2000), the *2dF* (Hawkins et al. 2003) and SDSS (Budavari et al. 2003) galaxy distributions as well as the *2QZ* QSO’s (Croom et al. 2001). However, the most luminous, and thus nearer, *2QZ* sub-sample ($18.25 < b_j < 19.80$) has a larger correlation length ($\sim 8.5 \pm 1.7 \ h^{-1} \text{ Mpc}$) than the overall sample (Croom et al. 2002), in marginal agreement with our $\epsilon = -3$ clustering evolution results.

The large spatial clustering length of our hard X-ray sources can be compared with that of Extremely Red Objects (EROs) and luminous radio sources (Roche, Dunlop & Almaini 2003; Overzier et al. 2003; Röttgering et al. 2003) which are found to be in the range $r_o \simeq 12 - 15 \ h^{-1} \text{ Mpc}$. The possible association of EROs with high- z massive ellipticals and of luminous radio sources with protoclusters (for a review see Röttgering et al. 2003 and references therein) suggests that our hard X-ray sources could trace the high peaks of the underline mass distribution (see also Yang et al. 2003).

4. Conclusions

In this paper we explore the clustering properties of hard (2-8 keV) X-ray selected sources using a wide area ($\approx 2 \text{ deg}^2$) shallow [$f_X(2 - 8 \text{ keV}) \approx 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$] XMM-*Newton* survey. Using an angular correlation function analysis we measure a clustering signal at the $\sim 4\sigma$ confidence level. Modeling the angular correlation function by a power-law, $w(\theta) =$

$(\theta_o/\theta)^{\gamma-1}$, we estimate $\theta_o = 48.9^{+15.8}_{-24.5}$ arcsec and $\gamma = 2.2 \pm 0.30$. Fixing the correlation function slope to $\gamma = 1.8$ we estimate $\theta_o = 22.2^{+9.4}_{-8.6}$ arcsec. Using a variety of luminosity functions and evolutionary models the Limber's inversion provides correlation lengths which are in the range $r_o \sim 10 - 19 h^{-1}$ Mpc, typically larger than those of galaxies and optically selected QSO's but similar to those of strongly clustered populations, like EROs and luminous radio sources.

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Table 1: The hard X-ray sources correlation length (r_o in h^{-1} Mpc) for different pairs of (γ, ϵ) and for the different luminosity functions and evolution models. The last column indicates the predicted median redshift, from the specific luminosity function used. The bold letters deliniate the preferred cosmological model and the most updated luminosity function.

LF	Evol. Model	$(\Omega_m, \Omega_\Lambda)$	$r_o (1.8, -1.2)$	$r_o (1.8, -3)$	$r_o (2.2, -0.8)$	$r_o (2.2, -3)$	\bar{z}
Boyle	No evol.	(1,0)	11.5 ± 2.00	9.0 ± 1.5	7.3 ± 1.2	6.0 ± 1.5	0.45
Ueda	No evol.	(1,0)	9.5 ± 1.5	7.5 ± 1.0	6.5 ± 1.5	5.0 ± 1	0.40
Boyle	PLE	(1,0)	13.0 ± 3.0	10.0 ± 2.0	8.0 ± 2.0	6.8 ± 1.5	0.50
Ueda	PLE	(0.3,0.7)	13.0 ± 2.0	9.3 ± 1.6	9.0 ± 2.0	6.7 ± 1.5	0.45
Ueda	LDDE	(0.3-0.7)	19.0 ± 3.0	11.5 ± 2.0	13.5 ± 3	8.5 ± 2	0.75
Ueda	LDDE	(1,0)	15.0 ± 2.5	7.8 ± 1.5	11.0 ± 2.5	6.0 ± 1.5	0.80

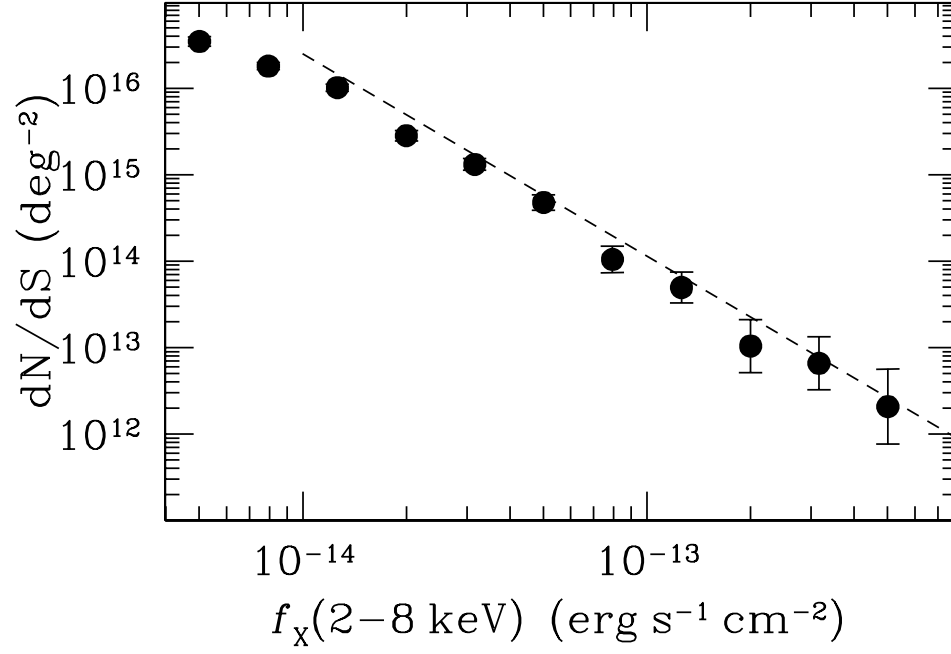


Fig. 1.— The hard band (2-8 keV) differential number counts from the present survey in comparison with those of Baldi et al. (2002; dashed line).

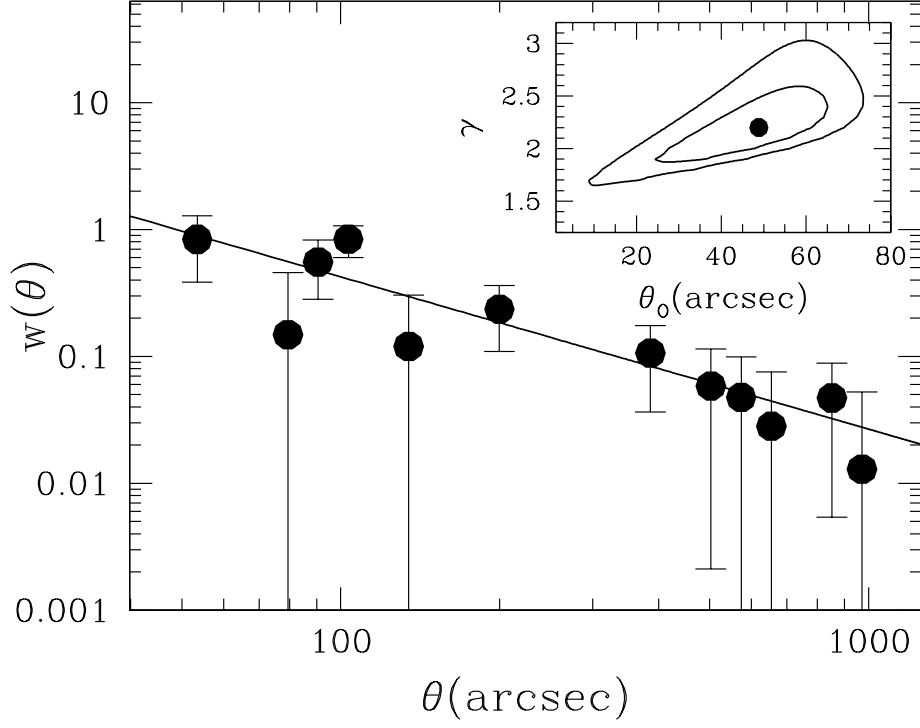


Fig. 2.— The two-point angular correlation function of the hard (2-8 keV) X-ray sources. The line represents the best-fit power law $w(\theta) = (\theta_0/\theta)^{\gamma-1}$ with $\theta_0 = 48.9$ arcsec and $\gamma = 2.2$. Insert: Iso- $\Delta\chi^2$ contours in the γ - θ_0 parameter space.

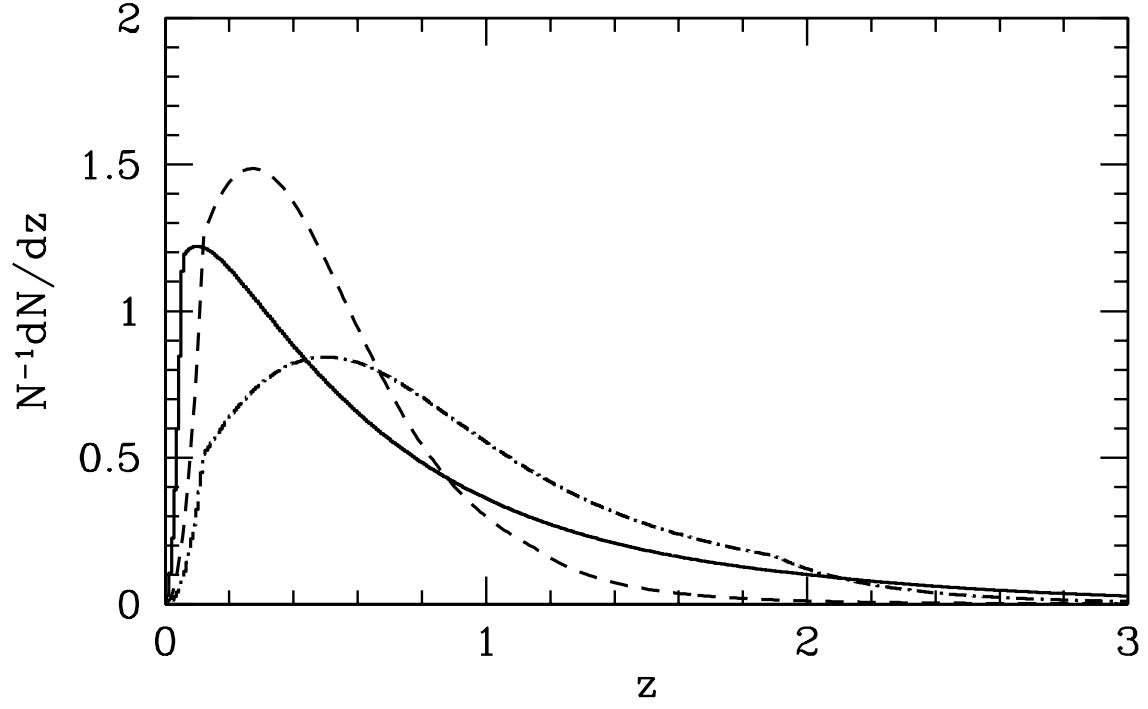


Fig. 3.— The predicted $N^{-1}dN/dz$ distribution for three different LF models: (a) Boyle et al. (1998) with PLE (continuous line), (b) Ueda et al (2003) with PLE (dashed line), (c) Ueda et al (2003) with LDDE (dot-dashed line).